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Field-circuit modelling of an advanced welding transformer with two parallel rectifiers*

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Abstract. The new topology of three-winding welding transformer is proposed. Each secondary winding is connected in parallel through the separate bridge rectifier to the welding arc. The main feature of the proposed device is parallel working of two secondary windings with different rated voltage. The advantage is nonlinear transformation ratio of current that provides unprecedented power efficiency. The self- and mutual leakage inductances, which are important in power conversion, are calculated by 2D FEA model. The operational current of the device is modelled numerically via P-Spice simulator. The proposed topology is up to 30% more power effective than conventional welding transformer provided that the leakage inductances of primary and secondary windings are correctly fitted. This transformer is used for manual arc welding.

Key words: Arc welding, double-bridge rectifier, leakage inductance, three-winding transformer, transformer equivalent circuit.

1. Introduction

A welding transformer with a rectifier is rather unusual electrical device, because it is loaded with complicated nonlinear load – an electric arc. The load is varying from the idle run to short circuit during welding cycle. It is necessary to have relatively high open circuit voltage of the transformer for the ignition of the arc and to keep operating current in a given range for stable arc. To meet these requirements, a topology of the uncontrolled double-bridge rectifier was proposed [1]. It contains a three-winding transformer with the primary winding 1 and two secondary windings *2* and *3* loaded with diode bridges 4 and 5 (Fig. 1).

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The bridge outputs are connected in parallel with the arc gap 6. Winding 2 and bridge 4 are designed to initiate and maintain stable arcing, while winding 3 and bridge 5 provide the main operating current. The open-circuit voltage of winding 2 is equal to 60-75 V, and the open-circuit voltage of winding 3 is approximately 40-45 V.

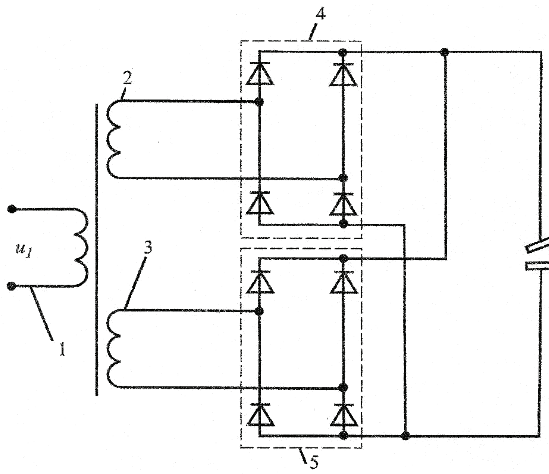

Fig. 1. Electric circuit of the double-bridge welding rectifier

The requirements imposed on devices for manual arc welding equipment can be formulated from the following information from the literature:

- The static external characteristic of the rectifier $U_L(I_L)$ (where U_L is the mean value of the load voltage, and I_L is the mean value of the load current) must be steeply falling (curve 1 in Fig. 2), i.e. the ratio of the short-circuit current I_{SC} to the operating (welding) current I_W, which determines the slope of the external characteristic, must be less than 1.5.
- The minimum instantaneous value of the welding current $i_{\min} > 0$ in any time of welding but the required value can only be determined experimentally.

2. Comparison of conventional and double – bridge rectifiers

The conventional single-phase rectifier for manual arc welding consists of a transformer with increased flux leakage, a diode bridge and a smoothing choke. The smoothing choke must be used in a single-phase rectifier to satisfy the condition $i_{\min} > 0$.

The external static characteristics (curve 1) of the conventional rectifier is shown in Figure 2. The dependence (straight line 3) of the operating arc voltage U_w on the arc current I_w for welding with a piece electrode is determined by the experimental expression:

$$U_W = 20 + 0.04 I_W. \quad (1)$$

The intersection of the external characteristic $U_L(I_L)$ with straight line 3 defines the conventional operating voltage $U_W = 25.2$ V of the arc and the operating current $I_W = 130$ A of the rectifier.

The external characteristic (curve 2) of the double-bridge rectifier with an operating current of 130 A and the external characteristics of the rectifier 4 (curve 4), and of the rectifier 5 (curve 5), obtained when they are operating together, are presented in Figure 2.

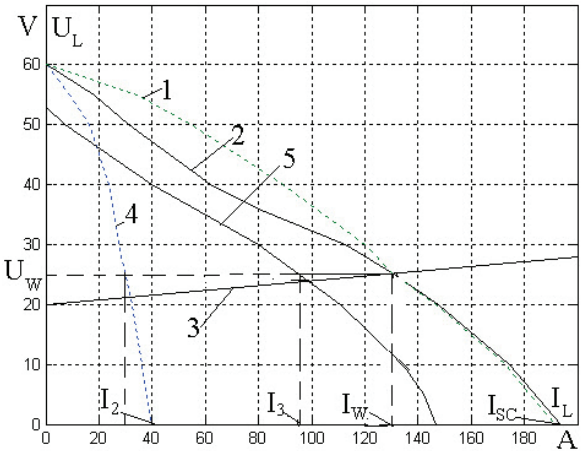

Fig. 2. External static characteristics of the conventional and double-bridge rectifier

The leakage inductances of welding transformer are chosen so that when $I_L > I_W$ the external characteristic of the double-bridge rectifier (curve 2) is identical with the external characteristic (curve 1) of a conventional rectifier having the same operating current, while the operating current of rectifier 5 exceeds the operating current of rectifier 4.

Moreover, the windings 2 and 3 provide a phase shift φ between their currents i_2 and i_3 (Fig. 3) thanks to properly chosen resistance and reactance, and as a result, the instantaneous values of the rectified current do not fall to zero during the welding process.

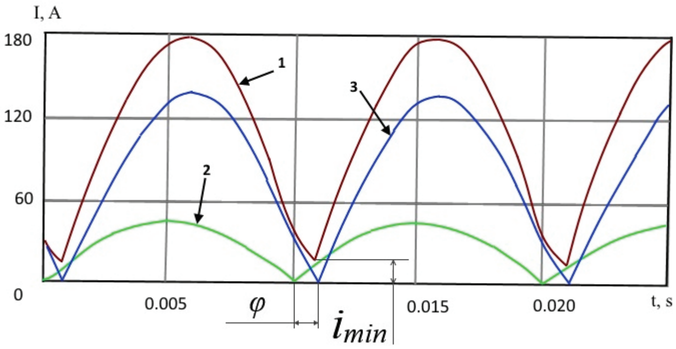

Fig. 3.Current diagrams of the rectifier (i is the load current, i_2,i_3 are the output currents of rectifier 4 and rectifier 5 under rectifier operating conditions)

This enables the smoothing choke to be eliminated in the single-phase double-bridge rectifier, thereby reducing its mass compared with the conventional rectifier. Experience shows that stable arcing is ensured at a relatively low phase shift φ of 5-10 degrees between the currents of 2 and 3 windings, if:

$$\frac{I_2}{I_3} \geq 0.3.$$

The mass and power consumption of such a rectifier are less than those of a conventional rectifier, since the main part of the welding current is the current of winding 3 and there is no a smoothing choke in the double-bridge rectifier. The mass of the smoothing choke in a conventional rectifier is up to 30% of the transformer mass.

3. The specific features of the double-bridge rectifier

A key feature of the double-bridge rectifier topology is a parallel connection of the secondary windings with different transformation ratios. The parallel working of two windings with different rated voltages is ensured by two factors:

- large magnetic leakage inductances and specially selected magnetic coupling factor for the leakage fluxes,
- limiting harmful circulating currents between secondary windings by diode bridges.

The key role of self- and mutual leakage inductances requires the use of finite element analysis for its prediction and optimization. The using of non-linear circuit elements requires numerical simulation for determination of operational characteristics of the double-bridge rectifier.

Magnetic leakage fluxes do not influence the saturation of the transformer core, as they are much lower than the main magnetic flux. Thus, inductive circuit parameters do not depend on the load. Due to this effect, we can avoid the strong coupling of circuit and field equations. In this study, we also neglect the eddy current losses and the frequency dependency of inductances.

It can be seen that the double-bridge rectifier has a nonlinear current transformation ratio $k_1 = I_w / 1_1$, which positively influences on the total power consumption. Neglecting the relatively small phase shift between the currents in windings 2 and 3 (i_2 and i_3) and the open circuit current, we can write for the primary current:

$$I_1 = \frac{I_2}{k_{12}} + \frac{I_3}{k_{13}} = I_{12} + I_{13}, \tag{2}$$

where

$$k_{12} = \frac{w_1}{w_2} = \frac{U_1}{U_{OC2}},, \; k_{13} = \frac{w_1}{w_3} = \frac{U_1}{U_{OC3}}, \; U_1 \text{ and } I_1$$

are RMS primary voltage and current, I_2, I_3 are RMS currents in windings 2, 3, U_{OC2}, U_{OC3} are open circuit voltages of windings 2 and 3, w_1, w_2, w_3 are turns of windings 1, 2, 3.
Experiments showed that for a phase shift φ between the currents i_2 and i_3 of 5°-10° the error of expression (2) is negligible small. Obtaining I_{12} from (2) we get the current transformation ratio of the rectifier as

$$k_I = \frac{I_2 + I_3}{I_1} = \frac{I_{12}k_{12} + I_{13}k_{13}}{I_1} = k_{12} + \frac{I_{13}}{I_1}(k_{13} - k_{12}). \tag{3}$$

It can be seen from the above expression that k_I is variable, since if the load of the rectifier is changed the ratio I_{13}/I_1 also changes (Fig. 2). When the rectifier is switched on at no-load state $I_{13} = 0$ and $k_I = k_{12}$, whereas under operating condition, when $I_{13}/I_1 = 0.7$, the value of k_I is increased by 30-35%. This value determines the reduction in the consumed power $S = U_1(I_W/k_I)$ compared with the conventional rectifier, which has a constant transformation ratio k_{12} and a consumed power $S = U_1(I_L/k_{12})$. The degree of reduction in the consumed power increases as the component I_{13} of the primary current increases. However, we cannot significantly reduce the voltage U_{03}, because this will reduce the slope of the external characteristic of the rectifier, which in turns reduces the arc stability.

The power consumption of a double-bridge rectifier:

$$S = U_1 I_1 \approx U_1\left(\frac{I_2}{k_{12}} + \frac{I_3}{k_{13}}\right), \tag{4}$$

It can be seen from this expression that the lower the voltage U_{OC3} the lower the power consumption S if $I_W = \text{const}$ and I_2/I_1 =const. Minimum U_{OC3} depends on the design of the transformer.

4. The equivalent circuit of a three-winding transformer

The proposed equivalent circuit (Fig. 4) differs from the well-known circuit of the three-winding transformer [1] by two features: firstly, the two secondary windings are not conductively coupled, and secondly, all inductances in the circuit are always positive. Therefore, the circuit is suitable for the standard simulation program (P-Spice). It is important that the circuit parameters have the clear physical sense and can be easily evaluated by FEA.

The similar, but a bit different approach was previously proposed in [2], where both secondary windings also are not conductively coupled, but there the ohmic losses were not taken into account. The papers [3] relies solely on experimentally estimated equivalent resistances. Furthermore, in the above papers the clear physical sense of the circuit parameters is not stressed, what make it difficult to analyze the effect of winding layout on the external characteristic and the energy consumption of the rectifier.

The equivalent circuit is obtained by replacing the three-winding transformer with two transformers: one with windings 1, 2 and the second with windings 1, 3 (further denoted as transformers 1-2 and 1-3) [1, 2]. The mutual impact of transformers 1-2 and 1-3 is modelled as a change of EMF on the terminals of their secondary windings by magnetic leakage fields.

Equations of three-winding transformer, referred to the secondary windings, for sinusoidal currents and voltages are:

$$E_{02} = r_{12} I_2 + j\omega L_{12} I_2 + \frac{r_1}{k_{12}k_{13}} I_3 + j\omega M I_3 + U_{load2}$$
$$E_{03} = r_{13} I_3 + j\omega L_{13} I_3 + \frac{r_1}{k_{12}k_{13}} I_2 + j\omega M I_2 + U_{load3}, \tag{5}$$

where I_2, I_3 are complex currents in windings 2 and 3, $\omega = 2\pi f$, f is the frequency, $j = \sqrt{-1}$, E_{02}, E_{03} are open circuit EMF in windings 2 and 3, L_{12}, r_{12} are leakage inductance and active resistance of transformer 1-2, L_{13}, r_{13} are leakage inductance and active resistance of transformer 1-3, r_1 is active resistance of winding 1, M - the mutual inductance of the leakage fluxes of transformers 1-2 and 1-3, U_{LOAD2} is complex voltage on the terminal of winding 2, U_{LOAD3} is complex voltage on the terminal of winding 3.

It is easy to verify that these equations coincide with the well-known equations of three-beam equivalent circuit of three-winding transformers, if Equations (5) will be referred to the primary winding. The advantage of Equations (5) in comparison with the well-known equations of a three-winding transformer is the physical meaning of their parameters.

Two formulas for calculation and measurement of the mutual inductance on leakage fluxes are obtained in [2]. The first one follows from the physical meaning of M:

$$M = \frac{L_{1,2+3} - L_{12} - L_{13}}{2k_{12}k_{13}}, \tag{6}$$

where $L_{1,2+3}$ is the leakage inductance of two-winding transformer with primary winding 1 and the secondary winding which consist of series-connected windings 2 and 3 (transformer 1-(2 + 3)). Another formula is based on the coincidence of the Equations (5) with the well-known equations of the three-beam equivalent circuit of a three-winding transformer:

$$M = \frac{L_{12} + L_{13} - L_{23}}{2k_{12}k_{13}}, \tag{7}$$

where L_{23} is the leakage inductance of transformer 2-3. All the leakage inductances in (6), (7) are referred to winding 1. Formulas (6) and (7) give the same results.

The degree of magnetic coupling of transformers 1-2 and 1-3 is characterized by the magnetic coupling factor for the leakage fluxes

$$k = \frac{M}{\sqrt{L_{12}L_{13}}}.$$

The magnetic coupling factor k is an indicator of how the winding arrangement affects the overall general power consumption. The mutual inductance M can be either positive, when the leakage flux in the winding 3 caused by the transformer 1-2 is directed opposite to the main core flux, or negative, if above fluxes has the same direction.

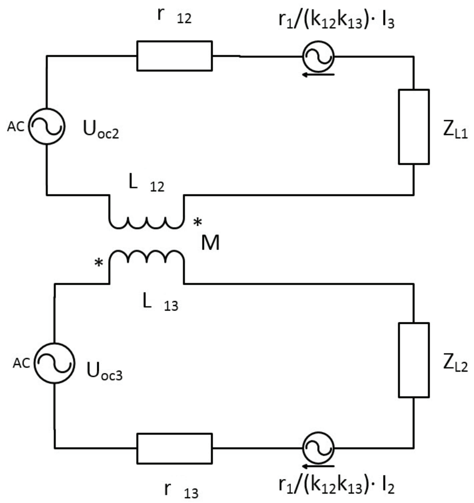

Fig. 4. Equivalent circuit of three-winding transformer

In the equivalent circuit in Figure 4 r_{12} and r_{13} are resistances of transformers 1-2 and 1-3 referred to the secondary side, Z_{L1}, $Z_{L2,}$ are load impedances. We also introduce dependent sources of EMF:

$$\frac{r_1}{k_{12}k_{13}} I_2 \text{ and } \frac{r_1}{k_{12}k_{13}} I_2 .$$

They take into account the change of the voltage at the terminals of the winding 3 and 2 due to a primary winding voltage drop of the transformer 1-3 and 1-2. The magnetic leakage fields in transformers 1-2 and 1-3 (short-circuit tests for transformers 1-2, 1-3) have been modeled by 2D FEA software QuickField [6]. The circuit's parameters L_{12}, r_{12}, L_{13}, r_{13} evaluate by 2D FEA model. For evaluating the magnetic leakage mutual inductance M we have made the FEA simulation of another short-circuit field in transformer 2-3 [2]. Calculation of transients in the circuit in fig. 1 have been made using the Microcap [7] software.

5. The calculation results

The equivalent circuit of three-winding transformer (Fig. 2) is used for studying the influence of the transformer design on the total power consumption. It was found, both analytically and experimentally, that an increase in the magnetic coupling of the leakage fluxes of the secondary windings reduces the operating current of the rectifier. The external characteristics obtained for $U_{OC2} = 65$ V, $U_{OC3} = 45$ V, $L_{12} = 4{,}3$ mH, $L_{13} = 1{,}5$ mH and different values of the coupling factor k are shown in fig. 6 as an example. As can be seen from this figure, the maximum operating current is obtained at a negative value of the coefficient $k = -0.3$. The calculations of transformer magnetic field by 2D FEA model has allowed to find a transformer design with a negative value of the coupling factor k.

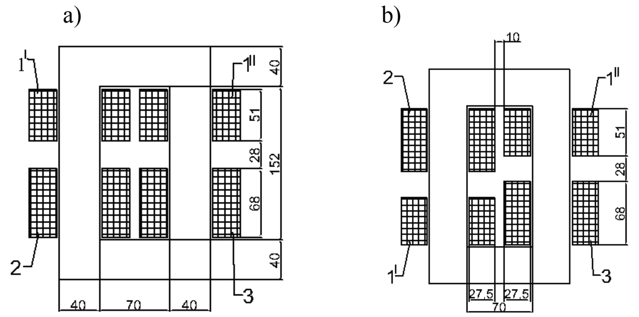

Fig. 5. Designs of the transformers

Two transformer designs in Figure 5a and 5b are considered. In these transformers primary windings consist of two series-connected sections $1'$ and $1''$. It was found that the conventional welding transformer (Fig. 5a) has $k > 0$. The new design of the transformer (Fig. 5b) has $k < 0$.

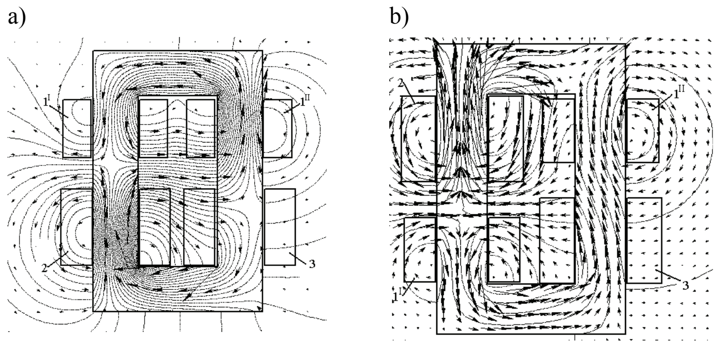

Fig. 6. The leakage fluxes of the transformers 1-2

The change in the sign of k for the transformer in Figure 5b can be explained by a change in the direction of the leakage flux in winding 3 caused by transformer 1-2. The leakage flux in winding 3 in Figure 6a is opposite to the leakage flux in the same winding in Figure 6b The direction of the main magnetic flux for both transformers in Figures 6a, 6b are counter clockwise.

On the bases of the investigations considered above a double-bridge welding rectifier with the operating current 200 A was developed. It has 30% lower power consumption than the conventional one. Its mass is 45% less than the mass of a conventional rectifier.

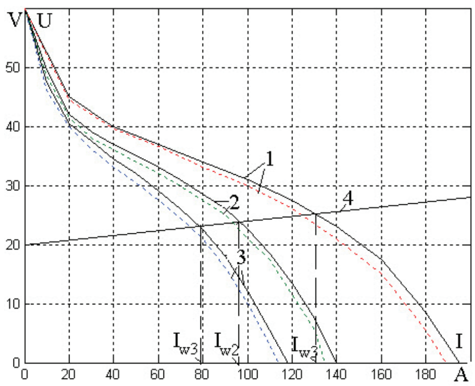

Fig. 7. The influence of the coupling factor for the leakage fluxes on the operating current of the rectifier: the curve 1 is for $k = -0.3$, the curve 2 is for $k = 0$, the curve 3 is for $k = 0.3$, and the curve 4 is the volt-ampere characteristics of a welding arc (1)

On the Figure 6 the computed (solid) and measured (dashed) curves are given together to demonstrate good agreement between the above method and experimental data.

References

[1] Sakhno L.I., *An investigations of double-bridge rectifiers with steeply falling external characteristics for supplying an electric arc*. Electrical Technology Russia 1: 96-104 (2002).
[2] Sakhno L.I., *Two-bridge welding rectifiers with single-phase transformers with a three-rod magnetic system.* Welding International l7(7): 565-569 (2003).
[3] Del Vecchio R.M. et al., *Transformer design principles: with applications to core-form power transformers*. CRC press (2010).
[4] Margueron X., Keradec J-P., *Design of equivalent circuits and characterization strategy for n-input coupled inductors*. IEEE Transactions on industry applications 43(1): 14-22 (2007).
[5] Margueron X., Keradec J-P., *Identifying the magnetic part of the equivalent circui of n-winding transformers*. IEEE Transactions on instrumentation and measurement 56(1): 146-152 (2007).
[6] Claycomb J.R., *Applied Electromagnetics Using QuickField and MATLAB*. Laxmi Publications, Ltd. (2010).
[7] Vladimirescu A., *The SPICE Book.* John Wiley & Sons, Inc., First Edition (1994).